3

AGE AND ORIGIN OF THE MURRAY RIVER AND GORGE IN SOUTH AUSTRALIA

By C. R. TWIDALE, J. M. LINDSAY[2] AND J. A. BOURNE[1]

ABSTRACT: The course of the Murray River in South Australia has been determined largely by geological structure. Following mid-Tertiary and early Pliocene marine sedimentation in the western Murray Basin, the ancestral Mt Lofty Ranges were rejuvenated in the middle Pliocene. A precursor of the Murray River developed a course near the ranges, mainly north-south but already branching eastwards to Overland Corner. This valley system was drowned by a late Pliocene marine transgression which deposited estuarine Norwest Bend Formation.

In the early to middle Pleistocene, the Pinnaroo Block emerged as a positive feature. 'Lake Bungunnia', which was formed at least partly by tectonic blockage, drowned the proto-Murray and occupied lowlands to the north, east and west of the Block.

Glacio-eustatic low sea levels of 100-150 m below present MSL in the middle and late Pleistocene, led to progressive headward recession and incision of the Murray Gorge, and to the cutting of the Murray submarine canyons across the continental slope.

The main valley-fill of Monoman and Coonambidgal Formations formed by aggradation to rising base-level during the post-glacial (Flandarian) rise in sea level.

INTRODUCTION

Problems posed by the age and origin of the Murray River in South Australia have engaged the attention of geologists for almost a century, since Tate (1885) proposed an explanation for the gorge tract between Overland Corner and Wellington.

Both in gross and in detail the South Australian sector of the river is notable for its seemingly erratic course. It runs in an overall westerly direction between the Victorian border and North West Bend, whence it turns through ninety degrees to flow southwards to the Southern Ocean. Several abrupt local changes of direction are superimposed upon this regional pattern, those at South (Great Pyap) Bend, Overland Corner, and Chucka Bend being the most prominent (Fig. 1).

Between the State Border and Overland Corner (the section 1 of Tate 1885) the Murray flows in an alluvial valley, which is characterised by scroll plains and abandoned river loops preserved as arcuate lagoons and swamps, and which is subject to seasonal flooding (Pl. 6). This modern flood plain is contained within older alluvial and lacustrine sediments of Late Cainozoic age (Fig. 2A).

At Overland Corner, the character of the river valley changes dramatically, for between that point and Wellington (Tate's section 2) the Murray flows in a comparatively narrow, deep and steep-sided trench or gorge (Figs. 2B, C, Pl. 7 & 8).

Though it varies from site to site the gorge is typically 30-40 m deep from the cliff top to the valley floor, and 600-1400 m wide, so that this gorge, like most others, is much wider than it is deep (Johnson 1932). The form of the bounding cliff varies systematically with its position vis à vis the river, being vertical where the winding river, which usually occupies only a small part of the gorge floor, impinges on the valley sides, and more gentle, even graded, on the inside of the river curves (Tate 1885, Twidale 1968 pp. 171-173).

The gorge is not, however, a simple feature, for the steep cliffs in many places give way to an open upper section so that an overall valley-in-valley form is displayed. The upper valley is mostly due to the greater erosion of such weaker lithological units as the Blanchetown Clay (Pl. 7, above), but in places may relate to remnants of a valley older than the gorge proper, as for example near Walker Flat.

[1] Department of Geography, The University of Adelaide, South Australia, 5000.
[2] Geological Survey of South Australia, Box 151 Eastwood, South Australia, 5063. Published with the permission of the Director-General of Mines and Energy.

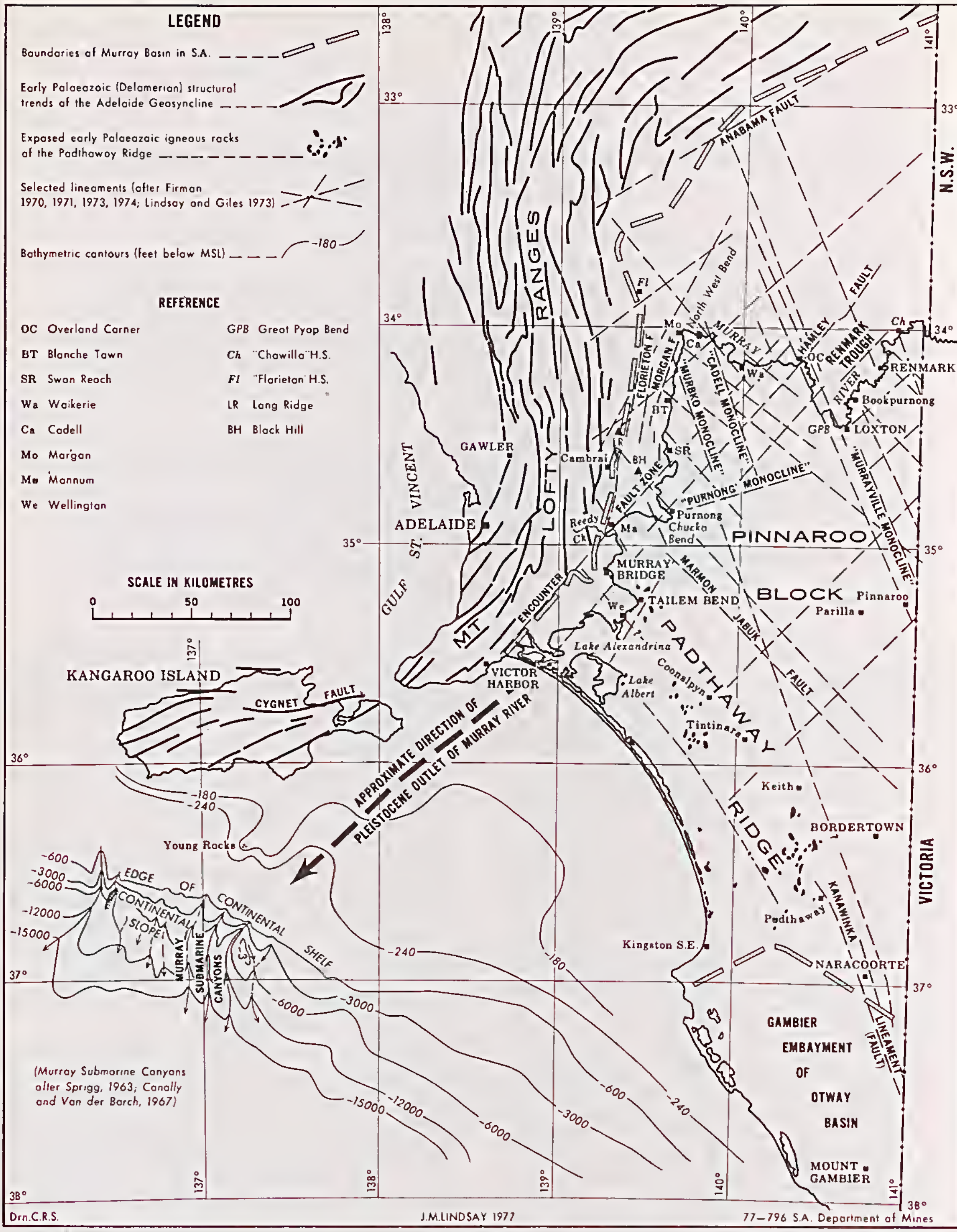


FIG. 1 — Structural elements influencing the course of the Murray River in South Australia.

STRUCTURAL CONTROL

Several writers have suggested that in broad view the course of the Murray is controlled by structural factors. Thus Hills (1956, p. 2) stated that far from being capricious, 'tectonic significance must be attached to every stretch of the River Murray, and that from the trends alone a clear indication of structure — the nature requiring to be investigated in each case — is provided.'

Regional Structure: The overall direction of the Murray from Morgan to the Murray mouth, and indeed its Pleistocene extension across the continental shelf, was controlled by the south to southwest Delamerian structural trends in the Late Precambrian to Early Palaeozoic rocks which form extensive outcrops in the Mt Lofty Ranges and which frame the western Murray Basin (Fig. 1: Delamerian trends after State Geological Map, 1:1,000,000, S.A. Dept. Mines & Energy, in prep.).

The sub-meridional course of the Murray south of Morgan lies close to the western border of the Murray Basin where the plains are lowest (Fig. 3). This is in part due to the late Cainozoic regional sagging or subsidence of this western area that accompanied continued uplift of the Mt Lofty horst block at that time (Sprigg 1952, p. 116). Yet the river does not run close to the eastern piedmont of the Mt Lofty Ranges, and is not diverted by those uplands as was suggested by Howchin (1929). A fault block of crystalline rocks which is part of the structural horst and yet is marginal to the topographic upland, underlies the western edge of the Murray Basin. Uplifted along the Florieton and Morgan faults (Figs. 1, 4) the block forms an area of high ground, and is here named the Cambrai Block (cf. 'Cambrai Plateau' of Firman 1964, 1973). The Cainozoic cover is relatively thin (less than 100 m) though of variable thickness, so that the basement rocks are nowhere far beneath the surface and many small outcrops of crystalline rocks occur, e.g. norite at Black Hill, granite at Long Ridge. The Murray River flows in the

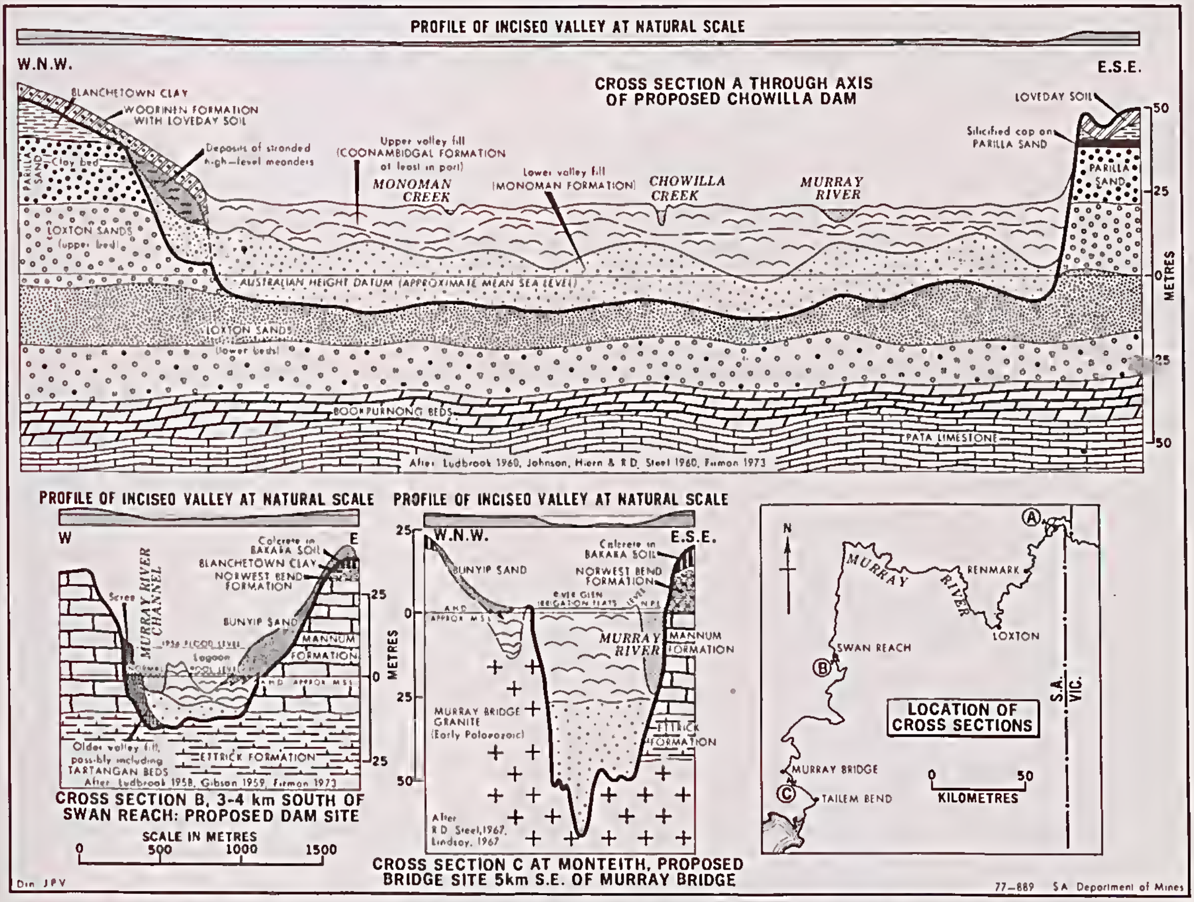


FIG. 2 — Cross sections through Murray River valley near Chowilla (A), Swan Reach (B) and Murray Bridge (C).

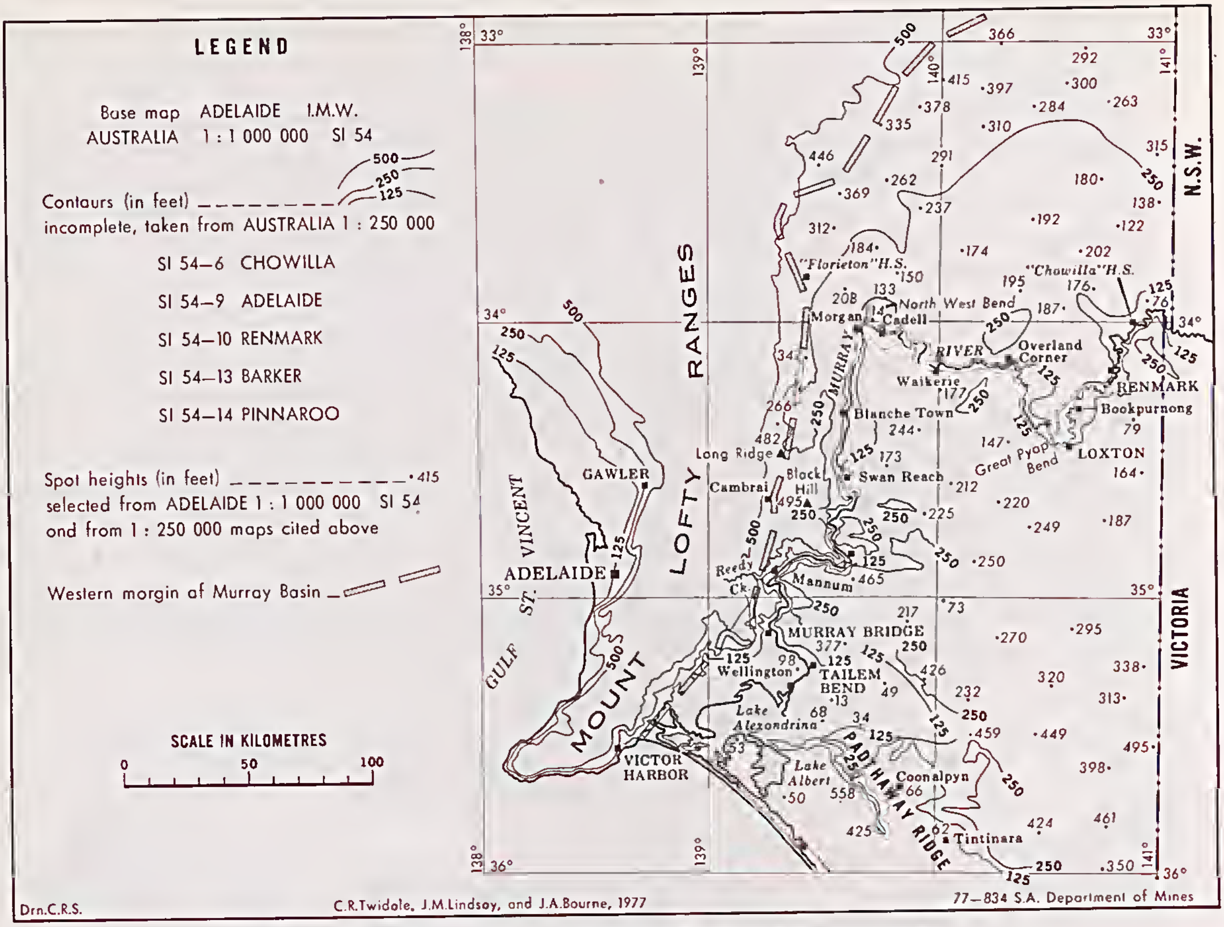


FIG. 3 — Topographic map of Murray Basin in South Australia.

depression between the east-facing fault scarps of the Cambrai Block and the gentle western decline that makes up the greater part of the Basin surface (Fig. 3).

Resurgent Tectonics: The transmission of basement structures to the overlying, essentially undeformed, sedimentary sequence is known as resurgent tectonics (Hills 1963, p. 333). Fractures in the crystalline rocks that underlie and delineate the Murray Basin form part of a continent-wide pattern of lineaments (Hills 1946, 1956, 1961). Recurrent joggling of the blocks so defined has caused similar fracture patterns to evolve in the flat-lying Basin sediments (Hills 1956, 1961, Firman 1970, 1971a, 1973, 1974, Lindsay & Giles 1973). These steeply dipping faults and joints have profoundly affected the course of the Murray.

Thus the major westerly diversion of the river between Purnong and Wellington, involving Chucka Bend and Tailem Bend, is related to the renewed uplift of the Marmon Jabuk structure (Fig. 1). In the present lakes area (section 3 of Tate 1885) the river is diverted northwesterly around the Padthaway Ridge or Horst. Again, the southerly course of the river between Morgan and Purnong runs in general parallelism, though it is not closely coincident, with the Morgan-Florieton fault zone.

Even outside the confines of the gorge, in the alluvial upper reaches of the Murray valley in South Australia, basement structures are reflected in the course of the river. The southwesterly trend of the river from Chowilla to Loxton follows the edge of the Renmark Trough (Fig. 1) which developed in the Middle to Late Palaeozoic (Thornton 1974). The Trough, the associated Hamley Fault, and the Encounter Fault Zone had Palaeozoic or even older origins, but were reactivated in the Cainozoic to produce gentle warping and fracturing in the Permian, Cretaceous and Tertiary sedimentary cover overlying displaced basement blocks. This appears to have had a subtle but decisive influence on the course of the river in this sector. Again, the northwesterly trend of the Murray from Loxton to Overland Corner

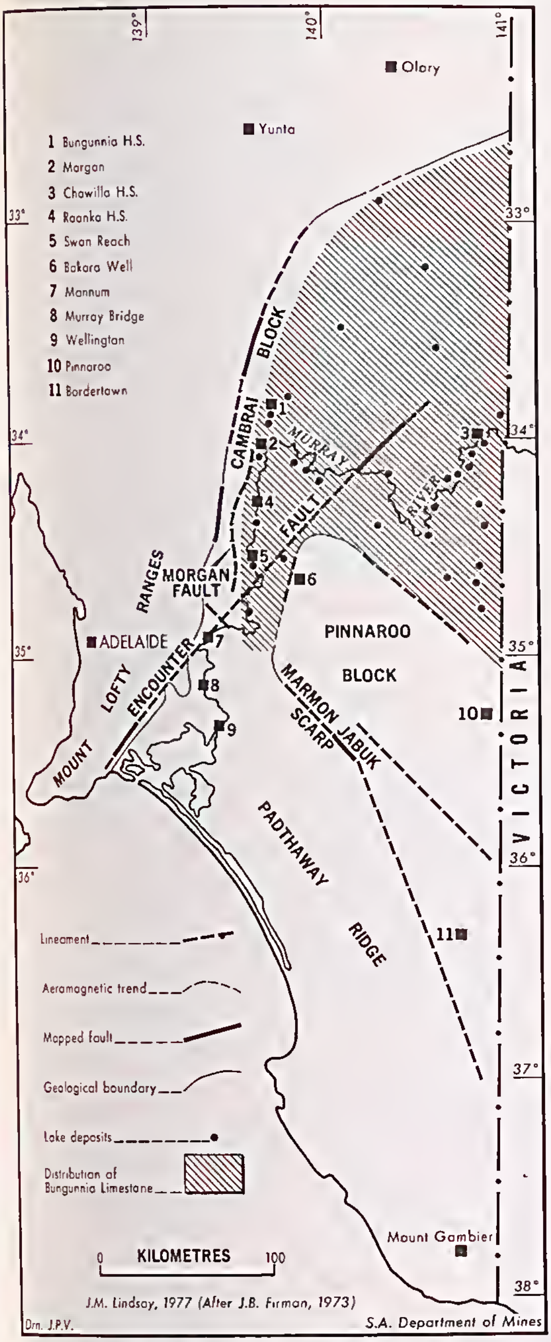


FIG. 4 — Extent of early to middle Pleistocene 'Lake Bungunnia' in South Australia.

follows the Murrayville Monocline (Spence 1958, O'Driscoll 1960, Lindsay & Giles 1973).

Major Joints: Within these broad regional trends the river and its valley wind about in what are at first sight hydraulic curves but which on closer inspection are controlled in considerable measure, as O'Driscoll (1960) pointed out, by NW.-SE. and NE.-SW. trending major joints developed in the Miocene limestones, possibly as a result of shearing along major basement structures (Fig. 1).

Thus the course of the river has been influenced at various scales by the structure of the basin sediments which in turn reflect structure in the underlying crystalline basement.

DEVELOPMENT OF THE MURRAY RIVER

Table 1 summarises various stages of development of the Murray River and its precursors in geological and stratigraphic perspective, which is mainly local, but includes a somewhat speculative correlation with major worldwide Quaternary glacio-eustatic events. The time scale is after Van Eysinga (1975), Tarling & Mitchell (1976), and La Brecque *et al.* (1977).

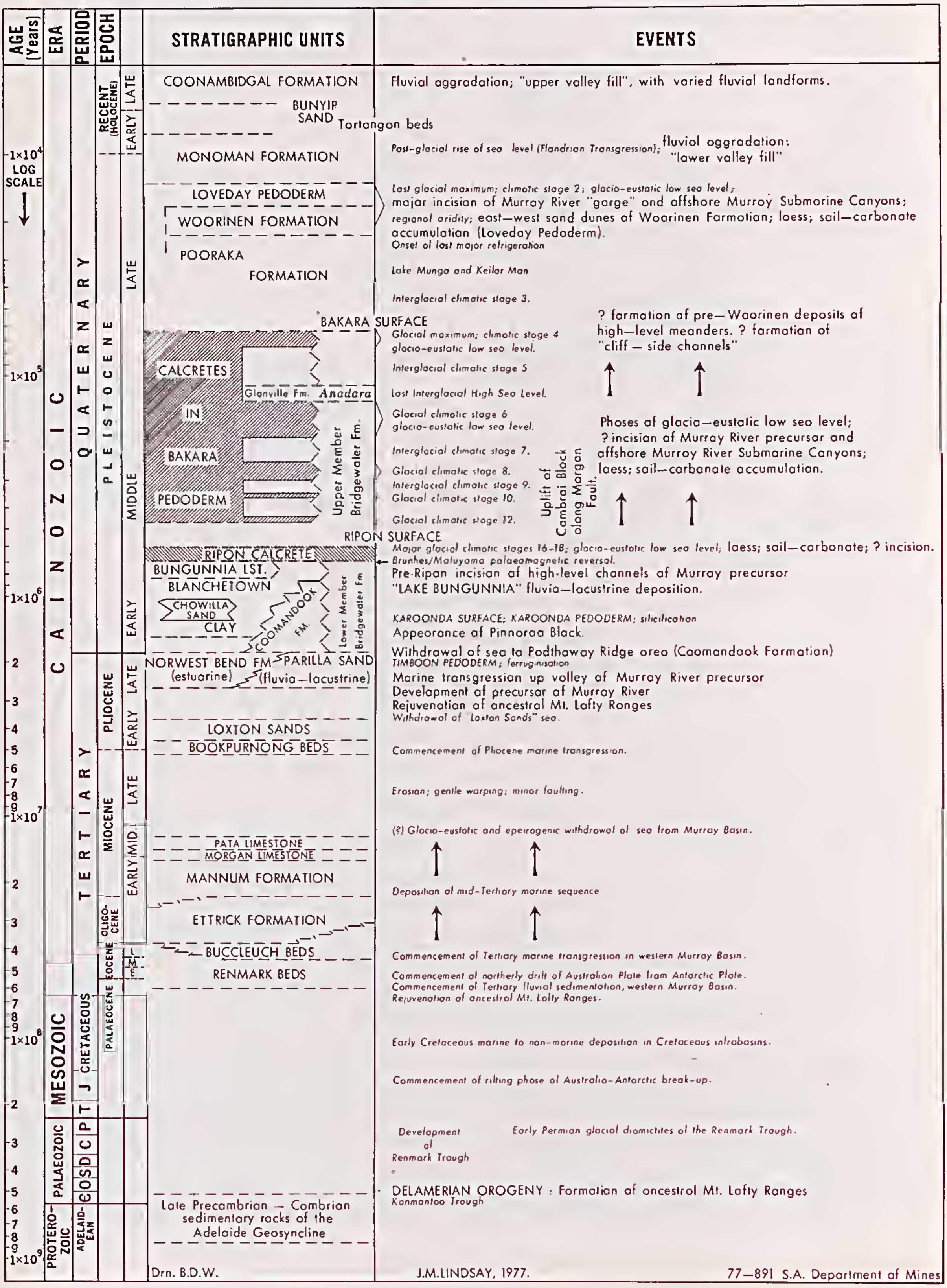
TERTIARY

Earlier Tertiary Events in the Murray Basin: Tertiary sedimentation in the western Murray Basin was initiated by uplift of the ancestral Mt Lofty Ranges along rejuvenated Delamerian fault-trends, probably in the early Palaeocene, and thus preceding the separation and drifting of the Australian Plate from Antarctica (Weissel & Hayes 1972, Deighton *et al.* 1976). The oldest Tertiary sediments in the area are palynologically dated middle Palaeocene and are of fluvio-lacustrine origin, but unrelated to the present Murray River. In a borehole at Waikerie, quartz sands, gravels, and carbonaceous clays of this age were intersected at 305-332 m (Harris, in Lindsay & Bonnett 1973). In the Loxton 'Company Bore', further southeastwards into the Basin, and away from the marginal ranges, carbonaceous silts at 487-515 m comprising the basal part of stratotype Renmark Beds, are of the same age (Harris 1966, 1970).

Sagging of the trailing margin of the northward drifting continent led to progressive marine transgression into southern Australian sedimentary basins from the middle Eocene onwards. The sea had entered the Murray Basin in South Australia by the late Eocene, and deposition of fossiliferous sands, marls and limestones on this epicontinental marine shelf continued, at least in the deeper parts of the Basin, until the middle Miocene (Pata Limestone). Early to middle Miocene sandy limestones of Mannum Formation and Morgan Limestone are the characteristic cliff-forming rocks of the River Murray gorge-tract (Pl. 7 & Pl. 8 above) between Overland Corner and Tailem Bend (Ludbrook 1961, Giles 1972, Lindsay & Giles 1973).

In the Murray Basin, as in the other South Australian coastal Tertiary basins, this cycle of

TABLE 1
DEVELOPMENT OF THE MURRAY BASIN AND MURRAY RIVER IN SOUTH AUSTRALIA — STRATIGRAPHIC TABLE.



widespread marine sedimentation ended in the middle Miocene probably as a result of the combined effects of a glacio-eustatic fall in sea level associated with rapid growth of the Antarctic ice-cap (see Dorman 1966, Hollin 1962, 1969, Kennett *et al.* 1975, Shackleton & Kennett 1975, Savin *et al.* 1975) and epeirogenic uplift of the trailing continental margin.

Weathering, erosion, mild warping and block-faulting ensued through the middle to late Miocene. Lineaments formed then and subsequently in the mid-Tertiary limestones in relation to these faults, monoclines and joints, were later to influence greatly the course of the developing Murray River.

Pliocene Events: Early Pliocene transgressive marine and fossiliferous units comprise glauconitic fine sands and marls of the Bookpurnong Beds, and coarser quartz sands of lower Loxton Sands. These were succeeded by regressive fluvio-lacustrine upper Loxton Sands deposited as the 'Loxton' sea retreated (Fig. 2A). After a hiatus, estuarine oyster banks and fossiliferous sands of the Norwest Bend Formation were deposited as a result of a further warm-marine transgression in the late Pliocene (Ludbrook 1959, 1961, 1963). The distribution of Norwest Bend Formation was restricted to a comparatively narrow meridional depression extending to Morgan and northward, with already an easterly branch running through Waikerie to Overland Corner and Kingston-on-Murray (Fig. 5). Here, the Norwest Bend Formation grades into the non-marine, clayey quartzose Parilla Sand (Firman 1973, p. 15) which is typically developed on the Pinnaroo Block and in the Murray cliffs upstream from Bookpurnong. No doubt the Parilla Sand comprises, at least in part, the deposits of fluvio-lacustrine systems tributary to the Norwest Bend Formation estuary.

The Ancestral (Mid-Pliocene) Murray: The Norwest Bend Formation occupies a shallow north-south corridor or depression eroded in the Miocene limestones or the Loxton Sands. It delineates, and represents, the late Pliocene drowning of an initial valley cut by a south-flowing precursor of the Murray River in the topographic low which was caused by faulting and sagging near the western margin of the Murray Basin, as noted above (Sprigg loc. cit., Ludbrook 1961, p. 86).

What sort of river was this earliest Murray? Did it develop through headward erosion and gradually extend northward, or was it in effect an overflow from some inland lake? Whatever its origin some special circumstances must have obtained to account for the development of the ancestral

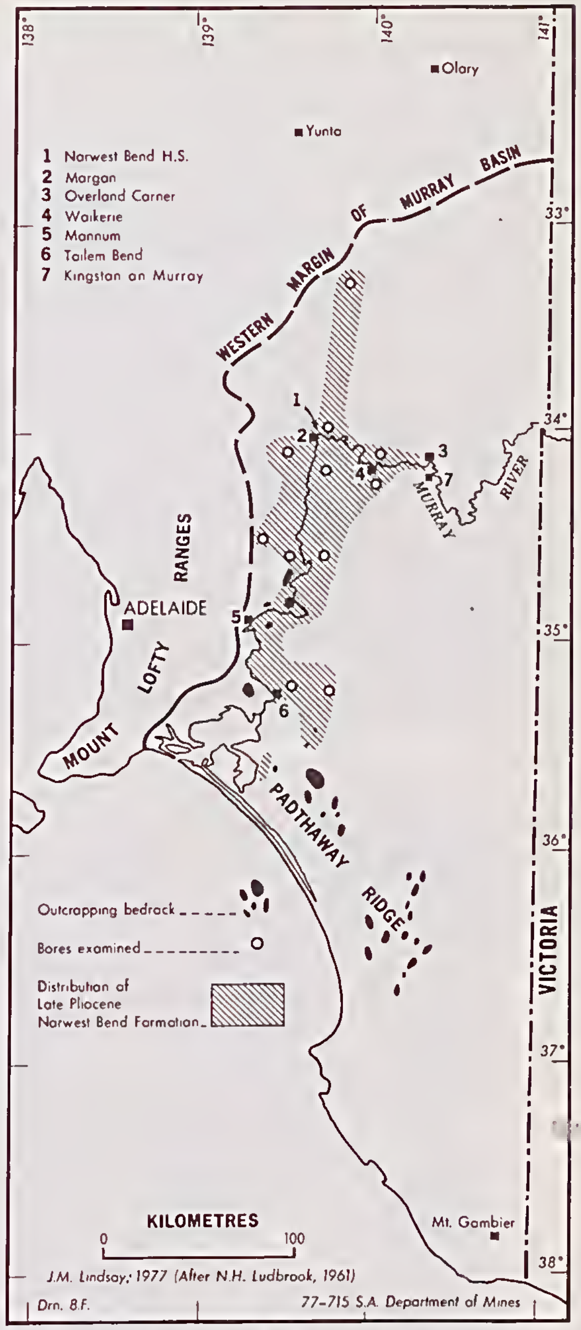


FIG. 5 — Distribution of Late Pliocene Norwest Bend Formation in Murray Basin in S.A.

Murray in the mid-Pliocene, enabling it to exploit the various structural weaknesses of the western Basin area, and erode a major valley.

The first advantage it had was that it was derived from, and fed by, the coalescence of streams emanating from the higher rainfall uplands to the west, the Mt Lofty Ranges. The shallowness of the crystalline basement would have assisted in developing runoff. This heavier runoff alone would have allowed the western consequent to incise its bed more rapidly than its eastern competitors and to become the master stream of the network.

Second, and reinforcing the excavation of the ancestral Murray valley, there may have been overflow from a Late Tertiary fluvio-lacustrine system (? 'Lake Nawait', see David 1950, p. 614; Firman 1971a, 1973) which occupied much of western N.S.W. and northwestern Victoria (Tate 1885, Pels 1969, Gill 1973a, Lawrence & Abele 1976). It is not known whether that system was connected to the ancestral Murray considered here. However the simple form of the high-level valley of the latter argues against any significant contribution to its development by catastrophic overflow from an inland lake, for such overflow would result in floods and in the development of broad braided channels comparable to those associated with the 'jokulhlaup' of periglacial regions (see Thorarinsson 1939), with the Channelled Scablands of Washington, northwestern U.S.A. (Baker 1973), and indeed with most of the river channels of arid and semi-arid Australia, but especially the Channel Country (see e.g. Bonython & Mason 1953 opp. p. 324) in consequence of adjustment to flood conditions.

Thus the presence of the impermeable rock uplands to the west together with the adjacent tectonic basinal depression appear to be the principal factors leading to the dominant development of the ancestral Murray.

It was to this shallow valley, and later to the estuary occupying it, that the adjacent areas were eroded and graded to develop the rolling topography of the Murray Surface (Twidale & Bourne 1975). The high plains surface, modified by Quaternary events and deposits, is extensively represented in the western and southern parts of the Murray Basin in South Australia, but in the north is buried by Quaternary alluvial and lacustrine deposits such as the Blanchetown Clay and the Bungunnia Limestone.

Quaternary Events

General Remarks: The Murray Gorge is cut through the base of the Norwest Bend Formation of late Pliocene age, and is therefore essentially a Quaternary feature. Following withdrawal of marine influence from the Norwest Bend Formation estuary to the Padthaway Ridge, near the Plio-Pleistocene boundary, the ancestral Murray was re-established. Incision of its gorge was undoubtedly the result of Pleistocene glacio-eustatic lowering of sea level, particularly during the intensified cyclic development of continental ice sheets during the past 900,000 years (Shackleton & Opdyke 1973, 1976). Table 1 shows various glacial and interglacial climatic stages in a time-framework after these authors. The local stratigraphic succession follows Firman (1967, 1969, 1973) and

DESCRIPTION OF PLATES

Plate 6

Above — Oblique aerial view eastwards across Renmark, showing meandering course of upper Murray River, S.A., in broad alluvial valley with riverine swamps and abandoned river-loops. Murray plains with east-west dunes in the background. (Photo: S. Aust. E. & W. S. Dept.)

Below — Vertical air-photo, Renmark, showing complex river forms of the broad alluvial valley of the upper Murray River, S.A., including meanders, abandoned river-loops anabranches and riverine swamps. Top of photo is east. (Photo: S. Aust. E. & W. S. Dept.)

Plate 7

Above — Murray River, Waikerie, within gorge tract; showing cliff-forming Morgan Limestone, and at the top slope-forming Blanchetown Clay capped by Bakara Calcrete. Saline seepages occur on the Blanchetown Clay. (Photo: E. P. O'Driscoll.)

Below — Murray River, Swan Reach; gorge tract with cliff of Mannum Formation and Morgan Limestone; Norwest Bend Formation and Bakara Calcrete at top. (Photo: C. R. Twidale.)

Plate 8

Above — Murray River, Walker Flat; gorge tract with cliff mainly of Mannum Formation; oyster beds of Norwest Bend Formation at top. (Photo: C. R. Twidale.)

Below — Murray River, 6.4 km northeast of Mannum; gorge-side and outer ridges of Mannum Formation, with 'cliff-side channels' between; lagoon and river channel beyond, looking northeast: note absence of cliffs in gorge-tract here. (Photo: J. M. Lindsay.)

Gill (1973a, b), but detailed correlation with the glacial chronology is still unproven and tentative.

Earth movements were at times significant in addition to glacio-eustasy. In the early Pleistocene, for example, the Pinnaroo Block (Figs. 1, 4) was established as a positive topographic feature bounded on the southwest by the Marmon Jabuk and Kanawinka (?fault) scarps and bordered on the west, north and east by riverine and lacustrine plains. On these lowlands, through which the ancestral Murray flowed, Blanchetown Clay and then the thin Bungunnia Limestone were deposited, the latter at least in 'Lake Bungunnia' (Firman 1965, 1971a, 1973) which largely drowned the early Pleistocene river (Fig. 4).

An Early to Middle Pleistocene Murray: Glacio-eustatic low sea levels caused the Murray to incise its bed, and erosion seems to have predominated, but fragments of the earlier Murray valley are preserved in places. Thus Firman (1973, p. 39) noted that 'below the Ripon Calcrete are remnants of an old drainage pattern which extends from Murray Bridge north as far as Morgan'. These 'fossil streams now stranded high in the Murray Cliffs' were seen by him to represent a 'drainage pattern . . . probably developing until such time as Pleistocene faulting along the Marmon Jabuk scarp severed the main stream course near Murray Bridge'. Firman maintained that subsequent blanketing by loess, and the formation of Ripon Calcrete, destroyed the continuity of this river system; but this is debatable.

Dating of the Ripon Calcrete, and hence of this drainage pattern beneath it, has been assisted by preliminary palaeomagnetic results from the Naracoorte-Robe area (Cook *et al.* 1977). These results, taken in stratigraphic context, suggest an age for the Ripon near to the Brunhes-Matuyama palaeomagnetic reversal (700,000 years). A notable glaciation ('one of the longest glaciations of the Pleistocene') is recorded by climatic stages 16-18 of Shackleton & Opdyke (1973), dated by them as 592,000-688,000 years B.P. Granted the association between glacio-eustatic low sea level, loess distribution, and calcrete formation (e.g. Firman 1967, p. 173), this is a reasonable possibility for the time of formation of Ripon Calcrete.

Extension and Incision of the Murray: During these lowerings of sea level by some 100-150 m compared with the present (Shackleton & Opdyke 1973, Chappell 1976), most of the continental shelf west of the Padthaway Ridge was repeatedly exposed. The Murray River extended its course across the shelf (cf. Sprigg 1947, Plan 4, Firman 1969, Fig. 104) and by generating turbidity currents, initiated the formation of the Murray submarine canyons (Fig. 1) down the relatively steep continental slope which drops 4,500 m in 60 km (Sprigg 1947, 1963, Conolly & Von der Borch 1967, Von der Borch 1968).

The lowered sea level also caused incision of the river, together with the development and headward recession of the gorge. The gorge-like character of the new valley was caused first by the calcareous nature and massive bedding and jointing of the Miocene strata in which the feature is mainly eroded, for these properties allow the development of steep cliffs and also inhibit the evolution of tributaries likely to eliminate the steep valley sidewalls. The aridity of the area also assists in this regard, and the undercutting achieved by the river itself, winding about on its own flood plain, is also partly responsible for the steep sidewalls of the valley. But it was the glacio-eustatic lowerings of sea level, the base level of erosion for all exoreic streams, that made possible the essential incision.

Though the Murray and its major tributaries incised their beds, and the regional water table fell, the predominantly calcareous nature of the Miocene strata that underlie most of the western Murray Basin caused the Murray Surface, graded to the Norwest Bend Formation estuary, to remain essentially intact. No doubt the aridity that prevailed through much of the Quaternary also helped in this regard.

The cutting of the gorge left the Murray Plains virtually untouched, but the lowering of the regional water-table allowed deep through-drainage and the development of a few comparatively small caves and numerous solution and collapse dolines. In general, however, because of the aridity and the impurity of the Miocene limestones, karst forms are poorly represented.

The river apparently did not erode the gorge in one phase but instead, in early to middle Pleistocene times, cut a comparatively shallow gorge which extended only as far upstream as Chucka Bend or thereabouts. This is indicated by the distribution of sediments laid down in the early to middle Pleistocene Lake Bungunnia (Fig. 4). Thus at this time the ancestral Murray still flowed in the original shallow valley as far south as Purnong. That shallow valley was drowned by Lake Bungunnia, which most likely developed by the damming effect of regional uplift along the Marmon Jabuk Fault (Figs. 1, 4; see also Mills 1964, Twidale & Bourne 1975). Further middle Pleistocene earth movements, on the Morgan Fault at the edge of the Cambrai Block, displaced Ripon

Calcrete during the formation of younger calcretes in the palaeosol, the Bakara Pedoderm (Firman 1973, pp. 32, 33).

Linear depressions interpreted differently by various authors, but here seen as erosional 'cliff-side channels' (Steel 1962, Frahn 1971, Thomson 1975) also formed during the incision of the gorge (Pl. 8 below, Fig. 6). Steel interpreted those at Teal Flat as slump structures. Thomson concluded that they are meander caves (Jennings 1970) modified by collapse and slumping. However, their general morphology and limited distribution between Scrubby Flat and Pompoota suggest that they were formed when the river was braided, rather than meandering. Moreover since braiding supersedes meandering when either gradient or discharge is increased, the channels, although of uncertain age, are best explained as due to localised steepening of the river bed (Leopold & Wolman 1957, Twidale 1966) consequent on renewed uplift of the Marmon Jabuk structure.

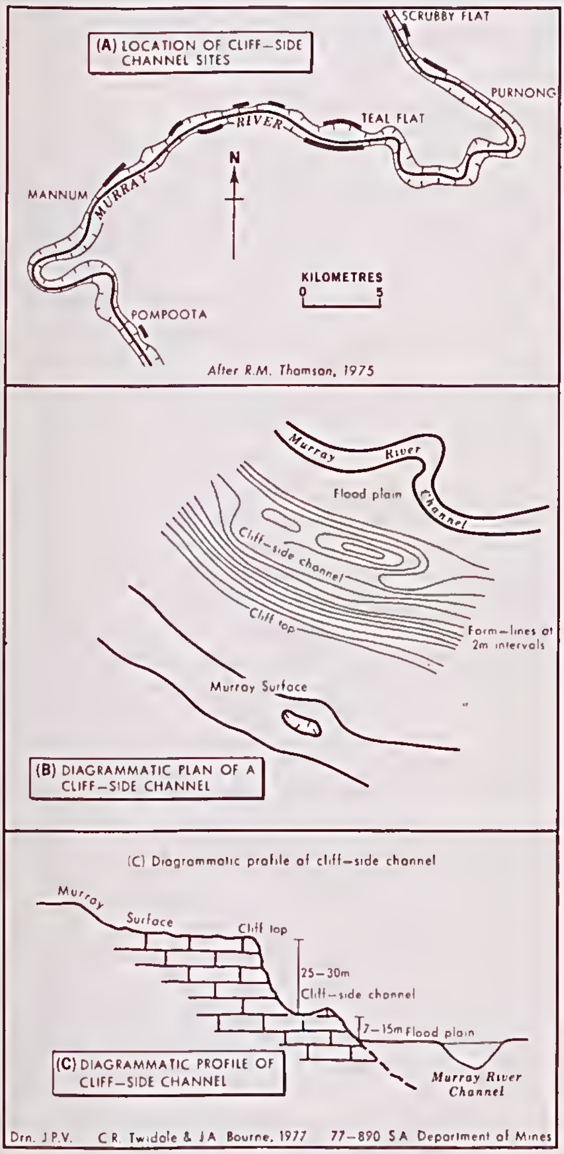


FIG. 6 — Location, diagrammatic plan and profile of 'cliff-side channels'.

The deepened gorge, which was ultimately incised as much as 65 m below the present valley floor (Fig. 2), extended headwards through the late Pleistocene, eventually breaching the limestones at Overland Corner which had been uplifted along the Murrayville Monocline.

Exhumation of Older Forms: During its Quaternary incision the river exhumed several small relics of ancient granitic landforms which had been buried by the advancing Oligo-Miocene seas and the sediments deposited therein. The river bottoms on granite at Murray Bridge (Sprigg 1952, Johns 1960, 1961) (Fig. 2C), and some 5 km upstream from Mannum an old domed inselberg, its surface pitted and grooved, is revealed from beneath the limestone cover. Granite boulders and other outcrops occur at several sites near Murray Bridge where the foundations of the new bypass bridge at Swanport are excavated partly in granite. Some of the right-bank tributaries, notably Reedy Creek, have similarly resurrected forms developed in Lower Palaeozoic crystalline rocks (Saies 1968).

Late Pleistocene and Post-Glacial Events: During the last glacial maximum (22,000-14,000 years B.P.) relatively arid conditions replaced the moist pre-glacial climate in southeastern Australia (Bowler 1976), but no doubt, then as now, the flow and erosive power of the Murray depended on precipitation and snow-melt on the Eastern Highland source-areas, irrespective of the aridity of the country traversed downstream. Growth of linear sand dunes was activated during this arid period (Bowler 1976), and the late Pleistocene east-west dunefields of Woorinen Formation in the Murray Basin (Lawrence 1966, Firman 1973) are assigned to this time. Horizons of silty and earthy carbonate in Woorinen Formation (and Pooraka Formation) comprise the Loveday Pedoderm (Firman 1973, Gill 1973b) and represent soil formation from widespread deposits of loess. Earthy carbonates from late phases of the Loveday Pedoderm in Woorinen Formation have yielded ^{14}C dates of 14,200 + 790 B.P., and 16,400 ± 450/560 B.P. (Gill 1973a). At the proposed Chowilla damsite (Fig. 2A), 'deposits of stranded high-level meanders' recognised by Firman (1973), relate to a precursor of the Murray River and are overlain by Woorinen Formation with Loveday Pedoderm.

The post-glacial rise of sea level (Flandrian Transgression) between 17,000 and 6,000 B.P. caused the Murray River to aggrade its valley to the rising base-level by depositing coarse-grained quartz sands of the Monoman Formation ('lower valley fill') (Firman 1966, 1973). The subsurface type sections of the formation are derived from foundation test holes drilled along the axis of the proposed Chowilla damsite, but the unit has also been penetrated in bridge-site drilling at Swan Reach and Murray Bridge (Fig. 2B, C). A femur of *Phascolonus* cf. *P. gigas* Owen, the giant wombat, and a vertebral centrum close to *Macropus ferragus* Owen, both extinct forms, have been identified from low in type Monoman Formation and tentatively dated late Pleistocene (Marshall 1973). Gill (1973a) recorded a ^{14}C age of 7,200 ± 140 B.P. for a log of *Eucalyptus largiflorens* (Black Box) from higher in Monoman Formation at the same locality, and dated the unit uppermost Pleistocene/lower Holocene as shown in our Table 1.

Younger valley fill of Coonambidgal Formation (Lawrence 1966, Firman 1971a, 1973) comprises fluvial clays, silts, and sands, generally finer-grained than Monoman Formation. Sub-fossil wood from basal Coonambidgal Formation at the Chowilla damsite yielded a ^{14}C date of 4,080 ± 100 B.P. (Firman 1967). Gill (1973a) recorded a 'disconformity between Coonambidgal Formation and Monoman Formation at Chowilla Damsite marked by fossil trees and oxidation of underlying sediments', correlated with a mid-Holocene phase of terrain instability and climatic oscillation. At Swan Reach, Firman (1971a, 1973, p. 42) described aeolian Bunyip Sand overlying shell-bearing Tartangan Beds ^{14}C-dated 6,020 + 150 B.P. by Tindale (1957), and underlying Coonambidgal Formation. It is likely that at least the initial accumulation of Bunyip Sand dunes and veneers took place during the same mid-Holocene phase.

The present flood plain is of course inundated at times of high water. In 1956 for instance the river flooded into the main street of Mannum and reached to the ceilings of ground floor rooms. The river then stood some 7 m above its normal level (Fig. 2B), but in prehistoric times, a flood dating from about 3,000 years ago clearly attained a higher level than that of 1956 (Mulvaney, Lawton & Twidale 1964).

The completion of the Murray Barrages in 1944, intended to control the ingress of sea water into the Murray system, caused a rise of about 0.6 m in the river level as far upstream as Blanchetown. Many river redgums have been drowned in consequence and many meadows and prime grazing lands have been converted to lagoons and swamps.

CONCLUSION

The development of the Murray River can be traced back some 3 m.y. to the middle Pliocene. The course of the river both in gross and in detail is determined largely by structure, but the essential gorge-like character of most of the valley in South Australia is the result of glacio-eustatic lowerings of sea level during the Pleistocene. The truncation of the river, the drowning of the lower part of the valley and the infilling of the lower part of the valley floor, all reflect the post-glacial rise in sea level.

REFERENCES

BAKER, V. R., 1973. Palaeohydrology and sedimentology of Lake Missoula flooding in eastern Washington. *Spec. Pap., geol. Soc. Am.* 144.

BONYTHON, C. W. & MASON, B., 1953. The filling and drying of Lake Eyre. *Geogr. J.* 119: 321-330.

BOWLER, J. M., 1976. Recent developments in reconstructing late Quaternary environments in Australia. In *The Origin of the Australians*, pp. 55-77. Eds. R. L. Kirk, A. G. Thorne. Human Biology Series No. 6. Humanities Press Inc., New Jersey, U.S.A.

CHAPPELL, J., 1976. Aspects of late Quaternary palaeogeography of the Australian-East Indonesian Region. *Ibid.*, pp. 11-22.

CONOLLY, J. R. & VON DER BORCH, C. C., 1967. Sedimentation and physiography of the sea floor south of Australia. *Sediment. Geol.* 1: 181-220.

COOK, P. J., COLWELL, J. B., FIRMAN, J. B., LINDSAY, J. M., SCHWEBEL, D. A. & VON DER BORCH, C. C., 1977. The Late Cainozoic sequence of southeast South Australia and Pleistocene sea level changes. *BMR J. Aust. Geol. Geophys.* 2: 81-88.

DAVID, T. W. E., 1950. *The Geology of the Commonwealth of Australia*. Ed. W. R. Browne. Vol. 1 of 3. Edward Arnold, London.

DEIGHTON, I., FALVEY, D. A. & TAYLOR, D. J., 1976. Depositional environments and geotectonic framework: southern Australian continental margin. *Aust. Pet. Explor. Assoc. J.* 15: 25-36.

DORMAN, F. H., 1966. Australian Tertiary palaeotemperatures. *J. Geol.* 74: 49-61.

FIRMAN, J. B., 1964. The Bakara Soil and other stratigraphic units of Late Cainozoic age in the Murray Basin, South Australia. *Q. geol. Notes, geol. Surv. S. Aust.* 10: 2-5.

———, 1965. Late Cainozoic lacustrine deposits in the Murray Basin, South Australia. *Ibid.* 16: 1-2.

———, 1966. Stratigraphy of the Chowilla area in the Murray Basin. *Ibid.* 20: 3-7.

———, 1967. Stratigraphy of late Cainozoic deposits in South Australia. *Trans. R. Soc. S. Aust.* 91: 165-180.

———, 1969. Quaternary Period. In *Handbook of South Australian Geology*, pp. 204-233. Ed. L. W. Parkin. Geol. Surv. S. Aust., Adelaide.

———, 1970. Structural lineaments in the Murray Basin of South Australia. *Q. geol. Notes, geol. Surv. S. Aust.* 35: 1-3.

———1971a. Riverine and swamp deposits in the Murray River tract, South Australia. *Ibid.* 40: 1-4.

———, 1971b. Renmark map sheet, Geological Atlas of South Australia, 1:250,000 series. *Geol. Surv. S. Aust.*

———, 1973. Regional stratigraphy of surficial deposits in the Murray Basin and Gambier Embayment. *Rep. Invest., geol. Surv. S. Aust.* 39.

———, 1974. Structural lineaments in South Australia. *Trans. R. Soc. S. Aust.* 98: 153-171.

FRAHN, D., 1971. Geomorphology of the Milendella area of South Australia. University of Adelaide B.A. (Hons.) Thesis, unpublished.

GIBSON, A. A., 1959. Site investigation for proposed bridge over River Murray — near Swan Reach. *Min. Rev., Adelaide* 108: 146-153.

GILES, S. D., 1972. Stratigraphic investigations of Tertiary sequences, western Murray Basin, South Australia. University of Adelaide B.Sc. (Hons.) Thesis, unpublished.

GILL, E. D., 1973a. Geology and geomorphology of the Murray River Region between Mildura and Renmark, Australia. *Mem. natn. Mus. Vict.* 34: 1-97, pls. 1-11.

———, 1973b. Palaeopedology of the Murray River Region between Mildura and Renmark, Australia. *Ibid.* 34: 241-252, pl. 32.

HARRIS, W. K., 1966. New and redefined names in South Australian Lower Tertiary stratigraphy. *Q. geol. Notes, geol. Surv. S. Aust.* 20: 1-3.

———, 1970. Palynology of Lower Tertiary sediments, southeastern Australia. University of Adelaide M.Sc. Thesis, unpublished.

HILLS, E. S., 1946. Some aspects of the tectonics of Australia. *Proc. R. Soc. N.S.W.* 79: 67-91.

———, 1956. A contribution to the morphotectonics of Australia. *J. geol. Soc. Aust.* 3: 1-15.

———, 1961. Morphotectonics and the geomorphological sciences with special reference to Australia. *Q. J. geol. Soc. Lond.* 117: 77-89.

———, 1963. *Elements of Structural Geology*. Methuen, London.

HOLLIN, J. T., 1962. On the glacial history of Antarctica. *J. Glaciol.* 4: 173-195.

———, 1969. The Antarctic ice sheet and the Quaternary history of Antarctica. *Palaeoecol. Afr.* 5: 109-138.

HOWCHIN, W., 1929. Notes on the geology of the Great Pyap Bend (Loxton), River Murray Basin, and remarks on the geological history of the River Murray. *Trans. R. Soc. S. Aust.* 53: 167-195.

JENNINGS, J. N., 1970. Ingrown meander and meander cave. *Aust. Geogr.* 11: 401-402.

JOHNS, R. K., 1960. Mobilong map sheet, *Geological Atlas of South Australia*, 1:63360 series. Geol. Surv. S. Aust.

———, 1961. The geology of the Mobilong military sheet (Explanation of the Geological Map). *Rep. Invest., geol. Surv. S. Aust.* 17.

JOHNSON, D., 1932. Streams and their significance. *J. Geol.* 40: 481-497.

JOHNSON, W., HIERN, M. N. & STEEL, R. D., 1960. Chowilla Damsite — geological investigations. Preliminary Report. *S.A. Dept. Mines Unpub. Rept.* 51/136.

KENNETT, J. P., HOUTZ, R. E., ANDREWS, P. B., EDWARDS, A. R., GOSTIN, V. A., HAJOS, M, HAMPTON, M. JENKINS, D. G., MARGOLIS, S. V., OVENSHINE, A. T. & PERCH-NIELSEN, K., 1975. Cenozoic palaeoceanography in the southwest Pacific Ocean, Antarctic glaciation, and the development of the Circum-Antarctic Current. In *Initial Reports of the Deep Sea Drilling Project* 29: 1155-1169. U.S. Govt. Printing Office, Washington.

LA BRECQUE, J. L., KENT, D. V. & CANDE, S. C., 1977. Revised magnetic polarity time scale for Late Cretaceous and Cenozoic time. *Geology* 5: 330-335.

LAWRENCE, C. R., 1966. Cainozoic stratigraphy and structure of the Mallee Region, Victoria, *Proc. R. Soc. Vict.* 79: 517-553.

——— & ABELE, C., 1976. Murray Basin. In *Geology of Victoria*, Chap. 8, Tertiary, p. 191-198. Eds. J. G. Douglas, J. A. Ferguson. *Geol. Soc. Aust. Spec. Publ.* 5.

LEOPOLD, L. B. & WOLMAN, M. G., 1957. River channel patterns: braided, meandering and straight. *Prof. Pap. U.S. geol. Surv.* 282-B.

LINDSAY, J. M., 1967. Palaeontological examination of samples. Site investigation for proposed Monteith Bridge. *S.A. Dept. Mines Unpub. Palaeo. Rept.* 12/67.

———, 1972. River Murray Salinity, Geomorphology Investigation, Lake Victoria area, N.S.W.: Stratigraphic and palaeontological notes with reference to the Chowilla area, S.A. *Ibid.* 72/149.

LINDSAY, J. M. & BONNETT, J. E., 1973. Tertiary stratigraphy of three deep bores in the Waikerie area of the Murray Basin. *Rep. Invest., geol. Surv. S. Aust.* 38.

——— & GILES, S. D., 1973. Notes on the *Lepidocyclina* Zone in Morgan Limestone along the Murray River, South Australia. *Q. Geol. Notes, geol. Surv. S. Aust.* 45: 1-7.

LUDBROOK, N. H., 1958. Stratigraphy and palaeontology of the Swan Reach Bridge site. *S.A. Dept. Mines. Unpub. Rept.* 46/31.

———, 1959. A widespread Pliocene molluscan fauna with *Anodontia* in South Australia. *Trans. R. Soc. S. Aust.* 82: 219-233, pls. 1-5.

———, 1960. Chowilla Damsite, River Murray.

Stratigraphy and micropalaeontology. *S.A. Dept. Mines Unpub. Rept.* 51/121.

———, 1961. Stratigraphy of the Murray Basin in South Australia. *Bull. geol. Surv. S. Aust.* 36.

———, 1963. Correlation of the Tertiary rocks of South Australia. *Trans. R. Soc. S. Aust.* 87: 5-15.

MARSHALL, L. G., 1973. Fossil vertebrate faunas from the Lake Victoria Region, S.W. New South Wales, Australia. *Mem. natn. Mus. Vict.* 34: 151-171, pls. 14-16.

MCGOWRAN, B., 1973. Rifting and drift of Australia and the migration of mammals. *Science* 180: 759-761.

MILLS, K. J., 1964. The structural petrology of an area east of Springton, South Australia. University of Adelaide Ph.D. Thesis, unpublished.

MULVANEY, J. D., LAWTON, G. H. & TWIDALE, C. R., 1964. Archaeological excavations at rock-shelter No. 6, Fromm's Landing, South Australia. *Proc. R. Soc. Vict.* 77: 479-516.

O'DRISCOLL, E. P. D., 1960. The hydrology of the Murray Basin Province in South Australia. *Bull. geol. Surv. S. Aust.* 35.

PELS, S., 1969. The Murray Basin. In *The Geology of New South Wales. Chap. 8*, pp. 499-511. Ed. G. H. Packham. *J. geol. Soc. Aust.* 16 (1).

SAIES, J., 1968. Geomorphology of the Mannum Falls area. University of Adelaide B.A. (Hons.) Thesis, unpublished.

SAVIN, S. M., DOUGLAS, R. G. & STEHLI, F. G., 1975. Tertiary marine paleotemperatures. *Bull. geol. Soc. Am.* 86: 1499-1510.

SHACKLETON, N. J. & KENNETT, J. P., 1975. Paleotemperature history of the Cenozoic and the initiation of Antarctic glaciation: oxygen and carbon isotope analyses in DSDP Sites 277, 279 and 281. *In* Kennett, J. P., Houtz, R. E., et al., *Initial Reports of the Deep Sea Drilling Project* 29: 743-755. U.S. Govt. Printing Office, Washington.

SHACKLETON, N. J. & OPDYKE, N. D., 1973. Oxygen isotope and palaeomagnetic stratigraphy of Equatorial Pacific Core V28-238: Oxygen isotope temperatures and ice volumes on a 10^5 year and 10^6 year scale. *J. Quat. Res.* 3: 39-55.

——— & ———, 1976. Oxygen-isotope and paleomagnetic stratigraphy of Pacific Core V28-239 Late Pliocene to Latest Pleistocene. *Mem. geol. Soc. Am.* 145: 449-464.

SPENCE, J., 1958. The geology of the Murray Basin. *Frome-Broken Hill Co. Pty. Ltd. Rept. No. 7500-G-27* (unpublished). S.A. Dept. Mines Open File Envelope No. 144.

SPRIGG, R. C., 1947. Submarine canyons of the New Guinea and South Australian coasts. *Trans. R. Soc. S. Aust.* 71: 296-310.

———, 1952. Geology of the South East Province, South Australia. *Bull. geol. Surv. S. Aust.* 29.

———, 1963. New structural discoveries off Australia's southern coast. *Australas. Oil Gas J.* 9: 32-42.

STEEL, R. D., 1962. Lower Murray dam sites — Teal Flat. *S.A. Dept. Mines Unpub. Rept.* 55-93

———, 1967. Southeast Freeway-River Murray crossing near Murray Bridge. Geological investigations — Progress Report No. 1: Feasibility and site selection stage. *Ibid.* 65/54.

TARLING, D. H. & MITCHELL, J. G., 1976. Revised Cenozoic polarity time scale. *Geology* 4: 133-136.

TATE, R., 1885. Notes on the physical and geological features of the basin of the lower Murray River. *Trans. R. Soc. S. Aust.* 7: 24-26.

THOMSON, R. M., 1975. The geomorphology of the Murray Valley in South Australia. University of Adelaide M.A. Thesis, unpublished.

THORARINSSON, S., 1939. The ice-dammed lakes of Iceland with particular reference to their value as indicators of glacier oscillation. *Geogr. Ann.* 21: 216-242.

THORNTON, R. C. N., 1974. Hydrocarbon potential of western Murray Basin and infrabasins. *Rept. Invest., geol. Surv. S. Aust.* 41.

TINDALE, N. B., 1957. Culture succession in south-eastern Australia from late Pleistocene to the present. *Rec. S. Aust. Mus.* 13: 1-49.

TWIDALE, C. R., 1968. *Geomorphology with special reference to Australia.* Nelson, Melbourne.

———, 1966. Late Cainozoic activity of the Selwyn Upwarp, northwest Queensland. *J. geol. Soc. Aust.* 13: 491-494.

——— & BOURNE, J. A., 1975. Geomorphological evolution of part of the eastern Mt Lofty Ranges, South Australia. *Trans. R. Soc. S. Aust.* 99: 197-209.

VAN EYSINGA, F. W. B., 1975. *Geological Time Table*, 3rd Edition. Elsevier Scientific Publishing Co., Amsterdam.

VON DER BORCH, C. C., 1968. Southern Australian submarine canyons: their distribution and ages. *Mar. Geol.* 6: 267-279.

WEISSEL, J. K. & HAYES, D. E., 1972. Magnetic anomalies in the southeast Indian Ocean. In *Antarctic Oceanology II: Australian-New Zealand Sector* 19: 234-249. Antarctic Research Series, A.G.U., Washington D.C., U.S.A.